

Application of Shock Capturing Method for Free Surface Flow Simulation

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ABSTRACT

The present study is a contribution to free surface flow simulation by numerical resolution of Saint-Venant's equations, which form a nonlinear hyperbolic system. For reasons of stability and accuracy, we apply finite volume method, based on Riemann problem's resolution using shock capturing schemes. Application tests for steady and unsteady flows confirm the capacity of these schemes to maintain stability and precision.

KEYWORDS: Free surface flow simulation, Shallow water equations, Saint-Venant, Finite volume, Riemann problem, Godunov's scheme, Limiters.

INTRODUCTION

The natural phenomena such as floods and inundations, as well as the damages which produce make the subject of several researches. Chow (1959), Henderson (1966) and Cunge et al. (1980) explored the free surface flow studies on rivers and in particular on channels. But the great improvement returns to Barré de Saint-Venant (1871) who established, for the first time, his one-dimensional model which governs flows in shallow water. It was successfully applied to simulate several phenomena such as; flood inundations (Ying et al., 2004), dambreaks (Fennema and Chaudhry, 1987) and tsunami waves (George, 2006).

Mathematically, such phenomena are governed by conservation laws which are represented by systems of non-linear hyperbolic PDEs. The nonlinearity in the Saint-Venant system presents shock and rarefaction waves. This theory and its approximation have been well detailed by Le Veque (Garcia-Navarro and Saviron, 1987), Lax-Wendroff (George, 2006) and Gallouet (George, 2004). Given the importance of these studies, several techniques have been developed in recent decades, using a variety of numerical methods. Among them, shock capturing finite volume schemes, based on Riemann problem solution, are developed in

this modest work.

Fabre (2001) explores this study by applying the one-dimensional Saint-Venant model. However, Le Veque (1998) illustrates various possible situations for analytical solutions of Riemann problems and the numerical treatment of shock and rarefaction waves.

Thus Riemann's approach is explored by Roe (1981) using first-order Godunov's scheme (Godunov, 1959) and second order Lax's scheme (Lax, 1972) which is a scheme without slope limiters. Van Leer (1977) and Warming and Beam (1975) introduce these slope limiters to prove the accuracy of such schemes.

Based on Fennema's and Chaudhry's works (Fennema and Chaudhry, 1987), Liggett and Cunge (1975) and MacDonald et al., (1997), we present various tests of steady and unsteady flows. Dambreak problems on dry bottom and wet bottom are studied. Thereafter, we treat the source terms represented by a flow over a concave bed.

MATHEMATICAL MODEL

Free surface flows, as their name indicates, are runoff flowings under the influence of gravity. They are managed by a system of PDEs (shallow water equations) (cf. Figure (1)). This one-dimensional model rises from two principles of conservation; that of mass:

$$\frac{\partial h}{\partial t} + \frac{\partial hu}{\partial x} = 0 \quad (1)$$

and momentum:

$$\frac{\partial hu}{\partial t} + \frac{\partial}{\partial x} \left(\frac{(hu)^2}{h} \right) + \frac{\partial}{\partial x} \left(g \frac{h^2}{2} \right) = -ghb(x)_x \quad (2)$$

where: hu is the unit discharge; h is the average depth of water; g is the gravitational acceleration and $b(x)$ is the bed slope.

One-dimensional vectorial form of this conservation law, with source term, is written as follows:

$$q_t + f(q)_x = \psi(x, t) \quad (3)$$

where q is the conservative variables' vector; $f(q)$ is the flux vector and ψ is the source term vector. Knowing that:

$$q = \begin{pmatrix} h \\ hu \end{pmatrix}, \quad f(q) = \begin{pmatrix} hu \\ hu^2 + \frac{1}{2}gh^2 \end{pmatrix} \quad \text{and} \quad \psi = \begin{pmatrix} 0 \\ -ghb(x)_x \end{pmatrix}$$

u is the average velocity,

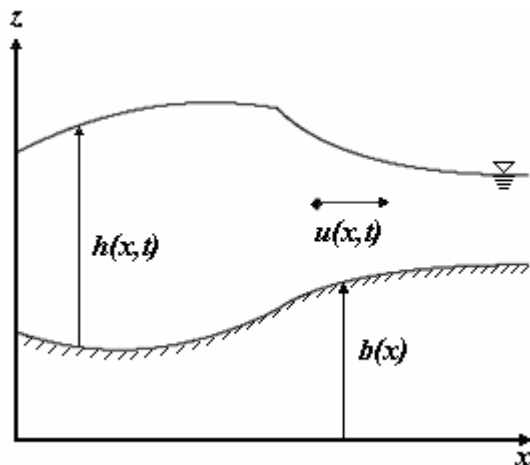


Figure 1: Different parameters in shallow water model

Shallow water equations represent a nonlinear hyperbolic system of PDEs, where the Jacobian matrix

$$J = f'(q) = \begin{pmatrix} 0 & 1 \\ -u^2 + gh & 2u \end{pmatrix} \quad (4)$$

is diagonalisable with real and distinct eigenvalues

$$\lambda^1 = u - \sqrt{gh}, \quad \lambda^2 = u + \sqrt{gh}.$$

RESOLUTION OF SAINT-VENANT EQUATIONS

A particular characteristic of hyperbolic systems is the existence of discontinuous solutions, such as shock waves. Several approaches are used to treat these cases. In the present study, we explore that based on Riemann problem's resolution.

Riemann Problem

Riemann problem represents a system of PDEs with special initial conditions which are constant on both sides of discontinuity, (cf. Figure (2)). Here, discontinuity is localised in $(x = 0)$.

If we neglect the source term, the Riemann problem is written as:

$$q_t + f(q)_x = 0 \quad \text{with};$$

$$q(x, 0) = \begin{cases} q_l & \text{if } x < 0 \\ q_r & \text{if } x > 0 \end{cases} \quad (5)$$

Therefore, the resolution of Riemann problem is to find an intermediate state q_m between the left state q_l and the right state q_r .

In Saint-Venant's system, we consider four configurations (Fabre, 2001), (cf. Figure (3)):

1. Two centred shock waves (from origin) which correspond to a collision of two waves.
2. Two centred rarefaction waves (from origin) which correspond to a separation of two waves.
3. One rarefaction wave propagates towards the left side and one shock wave propagates towards the right side which represents the configuration of a dambreak.
4. One shock wave propagates towards the left side and one rarefaction wave propagates towards the right side which represents a configuration of a hydraulic jump.

The first case (two shock waves) corresponds to the solutions of Saint-Venant's equations with initial conditions;

$$h(x, 0), \quad u(x, 0) = \begin{cases} u_l & \text{if } x < 0 \\ -u_l & \text{if } x > 0 \end{cases} \quad \text{with } u_l > 0$$

The solution is represented by two shock waves emanating from the origin, which create a stationary intermediate state, (cf. Figure (4)). The determination of this intermediate state is calculated by applying the jump's condition of Rankine-Hugoniot:

$$s(q^* - q) = f(q^*) - f(q) \quad (6)$$

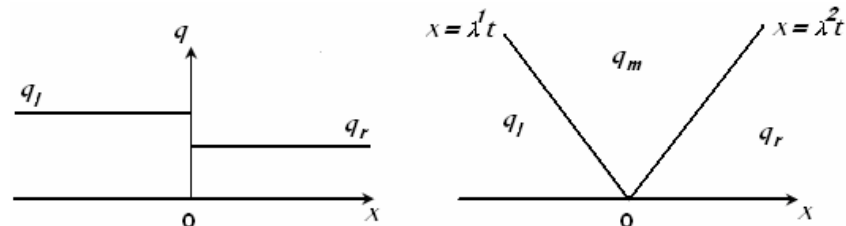


Figure 2: Illustration of Riemann's problem

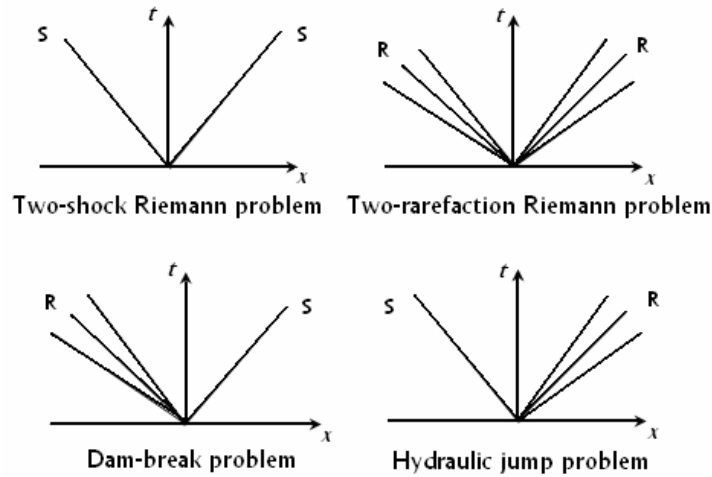
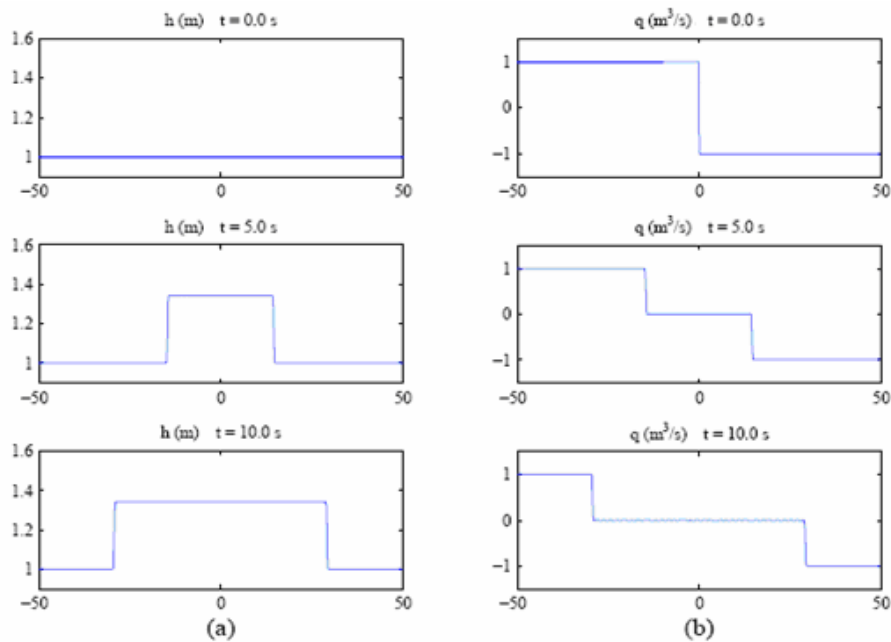


Figure 3: Four configurations of Riemann problem for Saint-Venant's equations

Figure 4: Riemann problem solutions for Saint-Venant equations with $u_l = -u_r > 0$ (a) depth, (b) discharge

This results in a system of two equations;

$$\begin{cases} s(h_* - h) = h_* u_* - hu \\ s(h_* u_* - hu) = h_* u_*^2 - hu^2 + \frac{1}{2}g(h_*^2 - h^2) \end{cases} \quad (7)$$

Graphically, this state represents the intersection of two Hugoniot's curves plotted from the left and right states, (cf. Figure (5)).

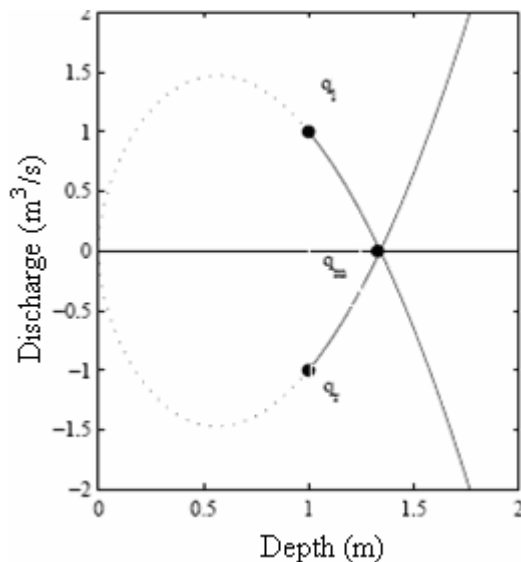


Figure 5: Construction of two-shock's solution for Riemann problem of Saint-Venant equations

In the second case (two rarefaction waves), the problem is posed with the following initial conditions;

$$h(x,0), \quad u(x,0) = \begin{cases} u_l & \text{if } x < 0 \\ -u_l & \text{if } x > 0 \end{cases} \quad \text{with } u_l < 0$$

This solution is schematized as (cf. Figure (6)).

This solution is calculated by applying the Riemann invariants relation such as;

$$\begin{aligned} w^1 &= u + 2\sqrt{gh} \\ w^2 &= u - 2\sqrt{gh} \end{aligned} \quad (8)$$

Intermediate state is given by:

$$\begin{aligned} u_m &= u_l + 2(\sqrt{gh_l} - \sqrt{gh_m}) \\ u_m &= u_l - 2(\sqrt{gh_r} - \sqrt{gh_m}) \end{aligned} \quad (9)$$

Graphically, the relation $q=f(h)$ is called the integrals curve and the intermediate state q_m represents the intersection of the two integral curves, (cf. Figure (7)).

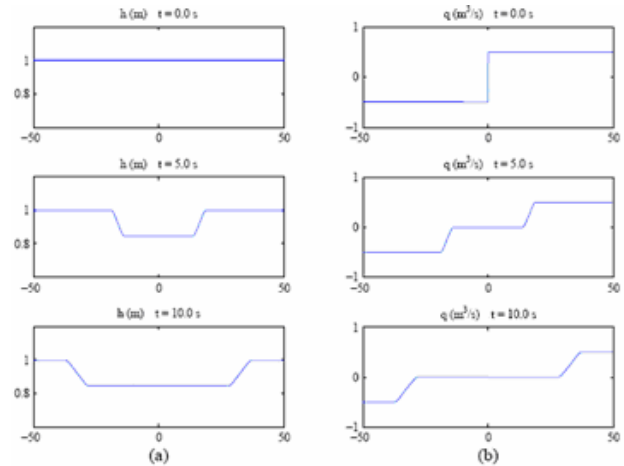


Figure 6: Riemann problem solutions for Saint-Venant equations with $u_l = -u_r < 0$ (a) depth, (b) discharge

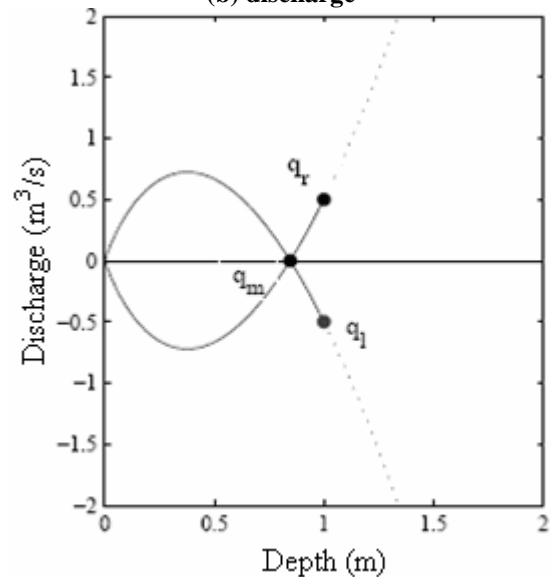


Figure 7: Construction of two-rarefaction waves solution for Riemann's problem of Saint-Venant equations

For the general case (rarefaction and shock waves) which illustrates a dambreak problem with the following initial conditions:

$$h(x,0) = \begin{cases} h_l & \text{if } x < 0 \\ h_r & \text{if } x > 0 \end{cases} \quad \text{with } (u,0) = 0,$$

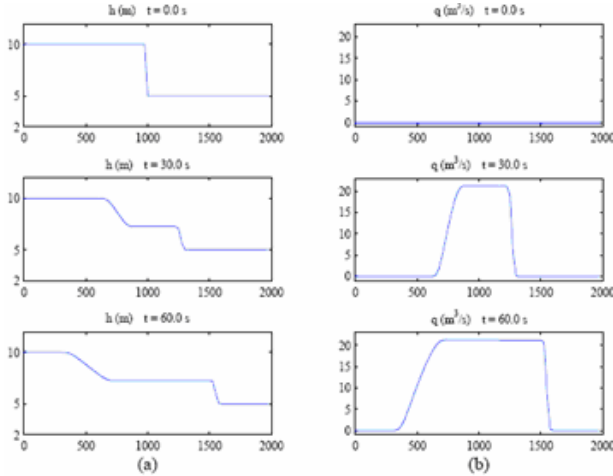


Figure 8: Riemann problem's solutions for a dam break (a) depth, (b) discharge

a shock wave propagates towards the right side and a rarefaction wave propagates towards the left side, (cf. Figure (8)), therefore the solution is obtained by applying Rankine-Hugoniot's relation for the shock wave and Riemann invariant's relation for the rarefaction wave, (cf. Figure (9)).

The treatment of the Riemann problem is made more flexible thanks to specific numerical methods named shock capturing methods which we will present hereafter.

Finite Volume Method (FVM)

Among all the numerical techniques, the finite volume method is well adapted to treat conservation laws, hyperbolic and nonlinear problems such as Saint-Venant's equations by applying the Riemann solver. This method is based on the discretization of the integral form, by subdividing the domain in a number of finite volumes (cells) (Le Veque, 2004). In each cell, the integral relations are applied locally and the exact conservation in each cell is realized, (cf. Figure (10)).

Each cell is defined by: $C_i = (x_{i-1/2}, x_{i+1/2})$

As shown in Figure (10), the value Q_i^n represents the approximation of the average value on the interval (i) at time t_n , we write:

$$Q_i^n \approx \frac{1}{\Delta x} \int_{x_{i-1/2}}^{x_{i+1/2}} q(x, t_n) dx \equiv \frac{1}{\Delta x} \int_{C_i} q(x, t_n) dx \quad (10)$$

The integration of equation (10) in time gives the general form of finite volume method applied to the

conservation laws;

$$Q_i^{n+1} = Q_i^n - \frac{\Delta t}{\Delta x} (F_{i+1/2}^n - F_{i-1/2}^n) \quad (11)$$

where $F_{i-1/2}^n$ is an approximation of the flux at $x=x_{i-1/2}$, so:

$$F_{i-1/2}^n \approx \frac{1}{\Delta x} \int_{t_n}^{t_{n+1}} f(q(x_{i-1/2}, t)) dt \quad (12)$$

First Order Godunov's Scheme

Classes of methods that provide a stable and consistent approximation to the numerical fluxes (12) are the Godunov-type methods. The original Godunov method (Godunov, 1959) is a first order upwind-type scheme, where Riemann problems are solved at each grid cell interface before each time step to determine the numerical flux for that time step. This approach is based on three following stages:

- Approximation of the solution by a piecewise constant function on each interval (cf. Figure (11));
- Solving in each interface $x_{i+1/2}$ Riemann problem;
- Evolving the solution by writing:

$$Q_i^{n+1} = Q_i^n - \frac{\Delta t}{\Delta x} [F_{i+1/2}^n - F_{i-1/2}^n]$$

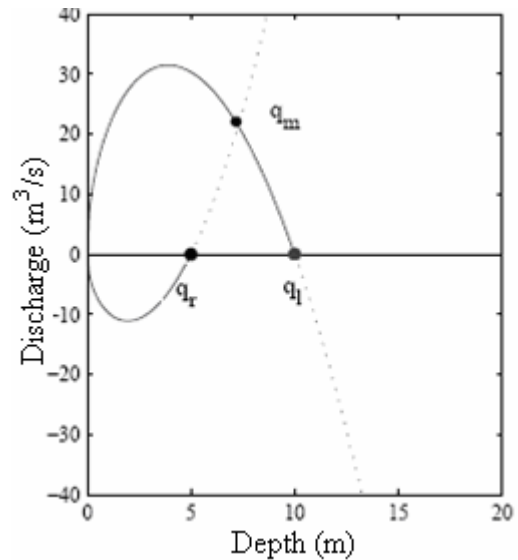


Figure 9: Construction of rarefaction-shock waves solution for Riemann's problem in dambreak problem

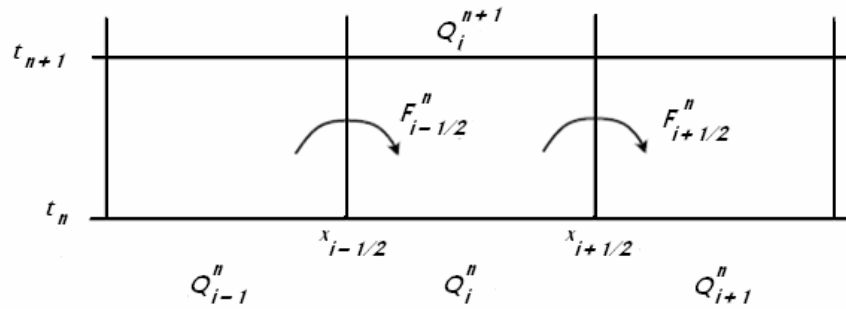


Figure 10: Principle of the finite volume method

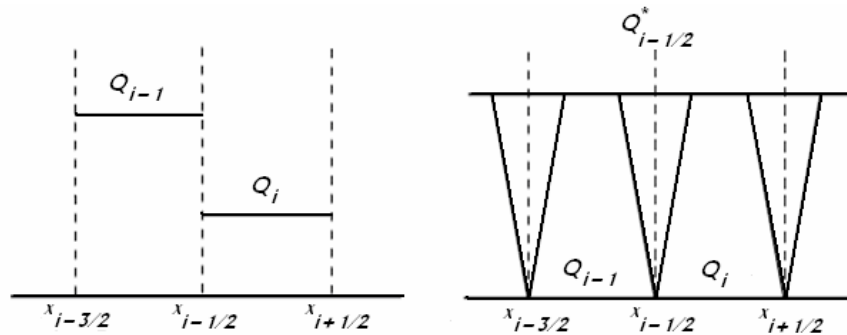


Figure 11: Principle of Godunov's scheme

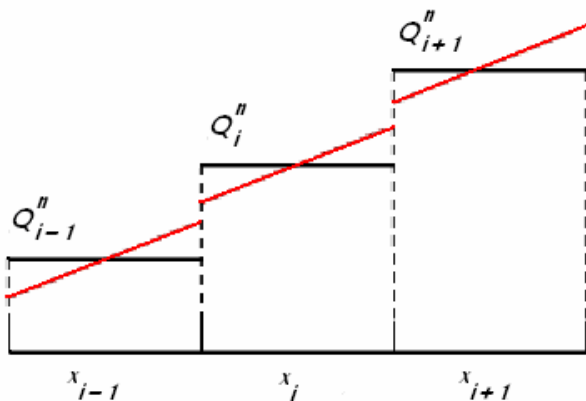


Figure 12: Slope's variable in each cell

High Order Schemes

Godunov's scheme is conservative. It respects the entropy condition, but it is a first order scheme and requires an iterative resolution in each time step. For more accuracy, Van Leer proposed adding a second order term (Van Leer, 1977), whereas Lax Wendroff (1960) and Roe (1981) developed other Riemann

solvers (Roe, 1981).

Roe's Solver. It is the most known and used solver. It is an approximate Riemann solver by replacing the exact Jacobian of Saint-Venant's system in each interval by a constant Jacobian. Roe gives this Jacobian as follows:

$$\hat{A}_{i-1/2} = \begin{bmatrix} 0 & 1 \\ -\hat{u}^2 + g\bar{h} & 2\hat{u} \end{bmatrix} \quad (13)$$

The depth and the average velocity are given by:

$$\bar{h} = \frac{1}{2}(h_{i-1} + h_i) \quad \text{and} \quad \hat{u} = \frac{\sqrt{h_{i-1}}u_{i-1} + \sqrt{h_i}u_i}{\sqrt{h_{i-1}} + \sqrt{h_i}} \quad (14)$$

Flux Limiters: The first order schemes give stable but less accurate solutions. However, the second-order schemes give accurate solutions but oscillate at discontinuities. The idea is, thus, to combine the advantages of these two schemes by applying flux limiters. The purpose of this idea is to improve the

behavior of the high order schemes. This technique appeared at the beginning of the Seventies in the *hybrid scheme* of Harten and Zwas (1972). More generally, we can combine any formula of first order flux $F_L(Q_{i-1}, Q_i)$ (such as upwind flux) by high order flux $F_H(Q_{i-1}, Q_i)$ (such as Lax-Wendroff) to obtain a flux limiter scheme, such as:

$$F_{i-1/2}^n = F_L(Q_{i-1}, Q_i) + \Phi_{i-1/2}^n [F_H(Q_{i-1}, Q_i) - F_L(Q_{i-1}, Q_i)]$$

- If $\Phi_{i-1/2}^n = 0$, it is a first order scheme;

- If $\Phi_{i-1/2}^n = 1$, it is a high order scheme.

So, the limiter represents a function $\Phi(\theta)$ in which θ is the variable's slope in each cell.

Slope Limiters: These are based on piecewise linear reconstitution (Le Veque, 2004), where the variable represents a piecewise linear function having a slope in each cell, (cf. Figure (12)), and we write:

$$\tilde{q}_i^n(x, t) = Q_i^n + (x - x_i) \theta_i^n$$

According to the evaluation of these slopes's functions, we set various schemes that are:

Schemes	Minmod	Superbee	Van Leer	Monotonized Centered MC
Slope's variable	$\phi(\theta) = \min(\theta, 0), \max(\theta, 0)$	$\max(0, \min(1, 2\theta), \min(2, \theta))$	$\phi(\theta) = \frac{\theta + \theta }{1 + \theta }$	$\max(0, (\min(1, \theta)/2, 2, 2\theta))$

Source term Treatment

When the effects of the source term are important (influence of the friction and bottom topography), we have to introduce the source term vector. We talk to about balance laws and we write;

$$q_t + f(q)_x = \psi(q, x, t)$$

where:

$$\psi(q, x, t) = \begin{pmatrix} 0 \\ -ghb_x \end{pmatrix}$$

Fractional Step Method: Le Veque (1998) explores

two principal numerical methods to treat these balance laws. These are the quasi-steady method and the fractional step method which splits the balance law into two equations;

- Homogeneous conservation law $q_t + f(q)_x = 0$;
- Ordinary differential equation ODE $dq/dt = \psi(q, x)$.

The solution is obtained by alternating between the solutions of these two equations in each time step.

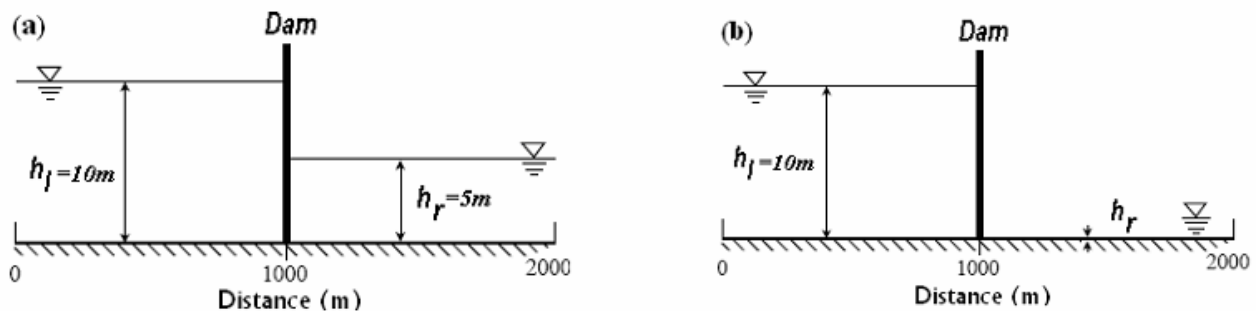


Figure 13: Initial conditions for dambreak test (a) on wet bottom (b) on dry bottom

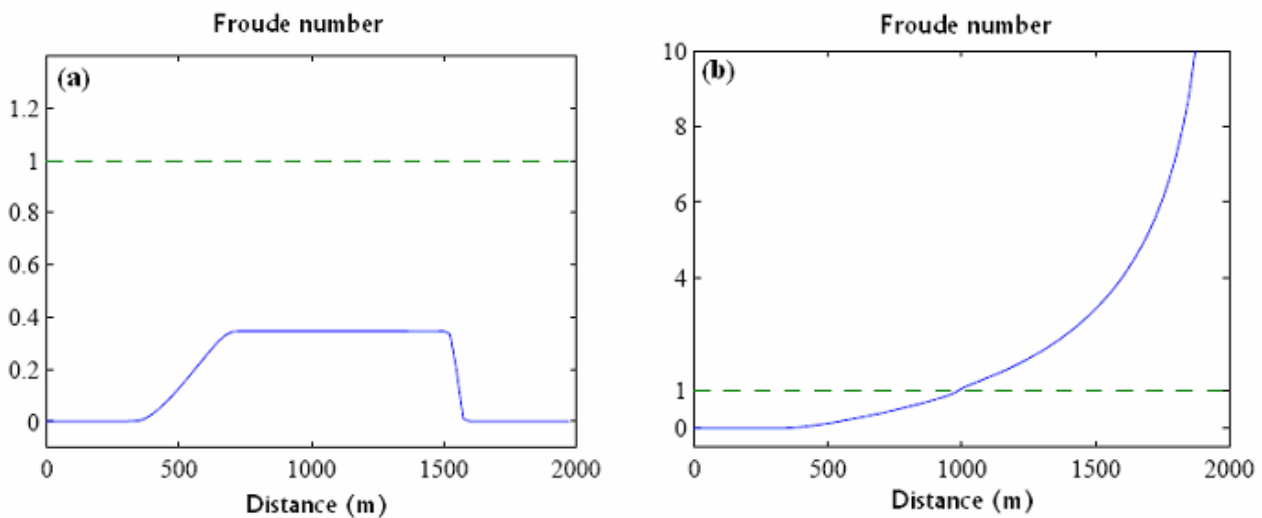


Figure 14: Froude's number analysis for dambreak test (a) on wet bottom (subcritical flow) (b) on dry bottom (supercritical flow)

NUMERICAL TESTS

The essential goal of these tests is to compare the various schemes, first order Godunov scheme and second-order slope limiter schemes. The comparative study involves the examination of steady flows

(dambeak) (Ying et al., 2004). Thereafter, we treat the source term which represents a flow over concave bed (Van Leer, 1977; Liggett and Cunge, 1975). We use a finite volume code "Clawpack" (Internet) (Conservation Law Package) by introducing the appropriate changes.

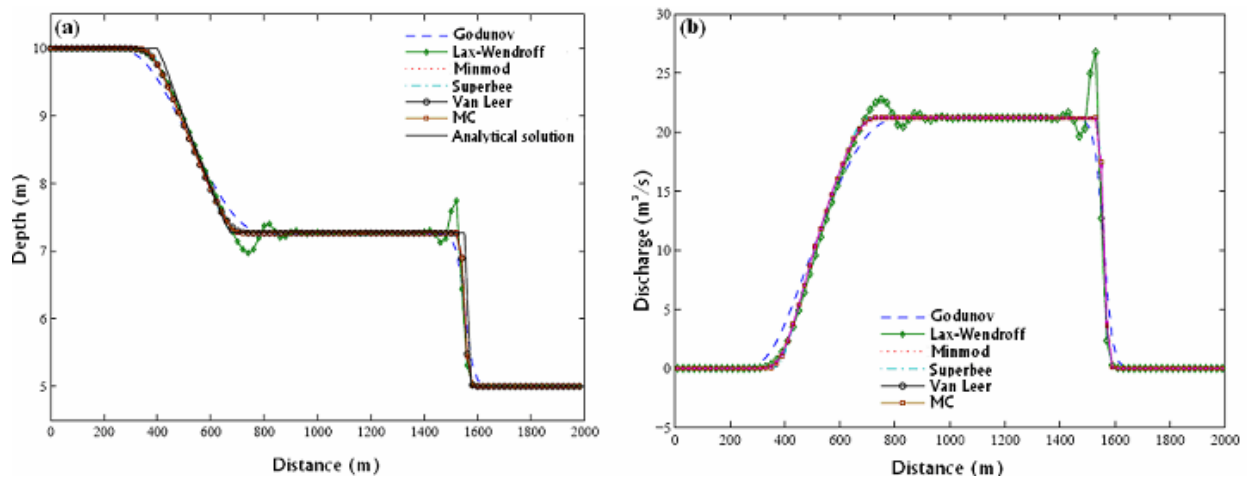


Figure 15: Comparison of different schemes – dambreak on a wet bottom (a) depth, (b) discharge

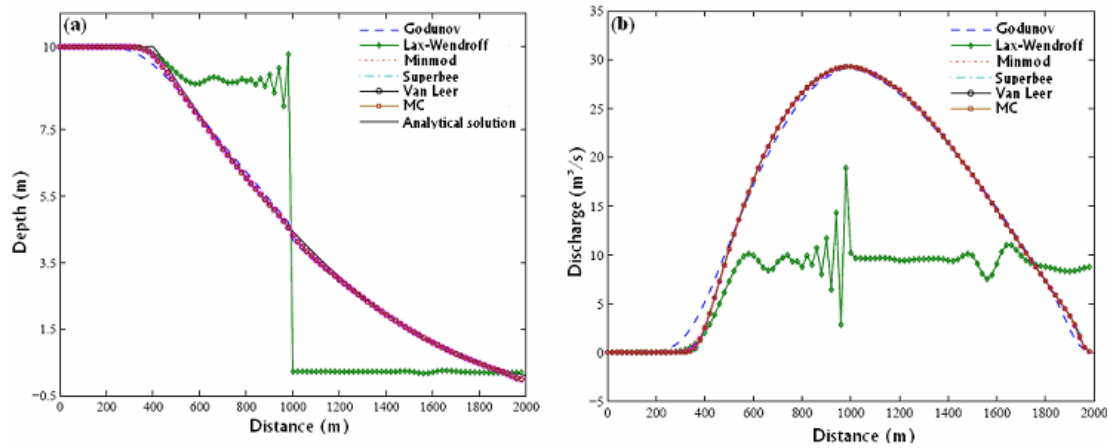


Figure 16: Comparison of different schemes – dambreak on a dry bottom (a) depth, (b) discharge

Dam Break Test

The first test is an examination of a dam break in a flat and horizontal channel (no friction effect), in two situations; on wet bottom and on dry bottom. We use a time step $\Delta t=0.1$ during 60s. The length of the domain is $x=2000\text{m}$. The breakpoint is located at $x=1000\text{m}$. The initial upstream depth is $h_l = 10\text{ m}$, while the depth in the downstream is initially $h_r=5\text{ m}$ (on wet bottom), and $h_r=0.0001\text{m}$ (on dry bottom). Initial unit discharge is null, $hu_l = hu_r = 0\text{ m}^2/\text{s}$ (cf. Figure (13)).

Froude's number analysis indicates that for the flow on a wet bottom, the flow regime is subcritical everywhere, while on a dry bottom, the flow regime is transcritical, since it passes from a subcritical to a torrential regime, (cf. Figure (14)).

After time $t = 60\text{s}$, we observe that Godunov's scheme diffuses near discontinuities, while Lax-Wendroff's scheme oscillates at shock and rarefaction waves, (cf. Figure (15)). Though, in the case of a dambreak on a dry bottom, the Lax-Wendroff's scheme fails completely, (cf. Figure (16)).

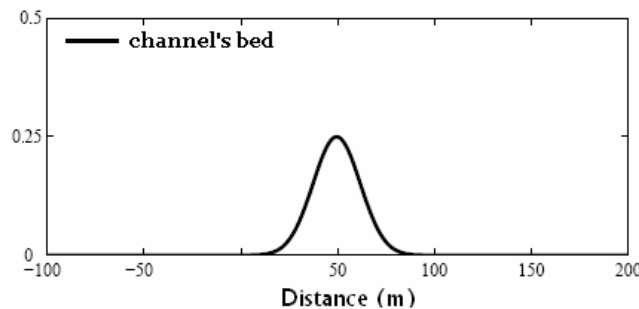


Figure 17: Bottom of the channel

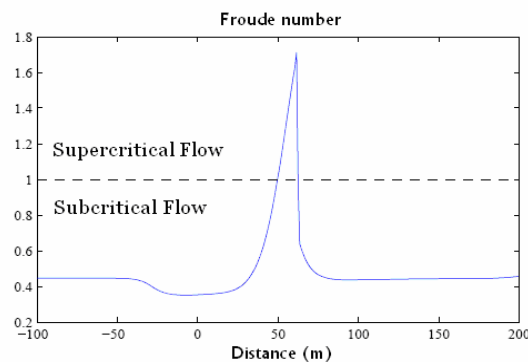


Figure 18: Evolution of Froude's number

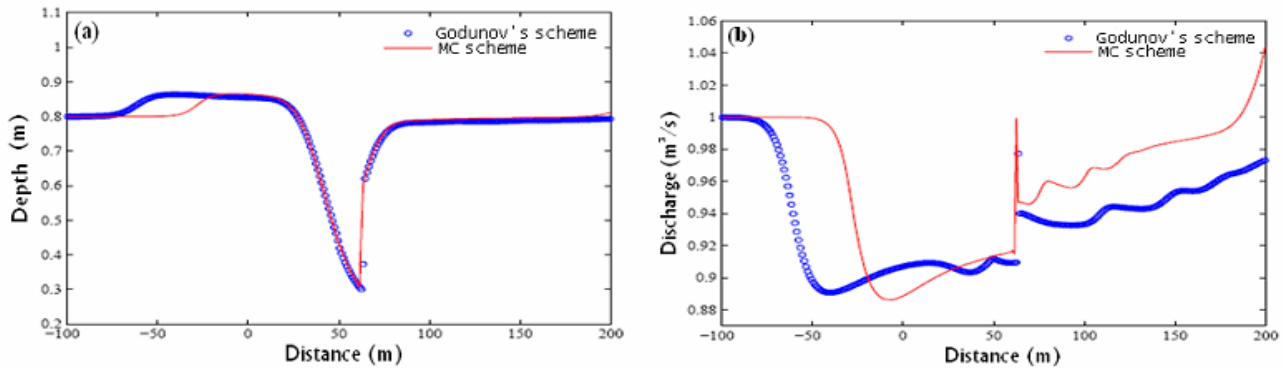


Figure 19: Comparison between Godunov and MC schemes (a) depth, (b) discharge

Flow over Concave Bed Test

In this case, we neglect the friction effect. The bed (cf. Figure (17)) is determined by a function $b(x)$ as;

$$b(x) = \begin{cases} 0.25 \exp(-33.75(x/100-0.5)^2) & \text{if } 0 < x < 100 \\ 0 & \text{otherwise} \end{cases} \quad (15)$$

Initial depth and discharge are respectively $h=0.8\text{m}$, $hu=1\text{m}^2/\text{s}$. The time of simulation is $t = 60\text{s}$ and the length of horizontal channel is $L=200\text{m}$ which is splitted into $\Delta x=1\text{m}$.

At the end of the simulation, we observe that a hydraulic jump was formed at the downstream of the bump.

Froude number's analysis shows that the flow mode is transcritical, since it moves from a subcritical to a torrential mode, (cf. Figure (18)).

Using fractional step method and comparing Godunov's and Monotonized Centered schemes, we note that the Godunov's scheme presents a numerical diffusion. However, discharge solution makes an artificial numerical jump (cf. Figure (19)).

CONCLUSION

In conclusion, we resume that Saint-Venant's equations represent a nonlinear hyperbolic conservation law. Such category has discontinuous solutions. Analytical resolution passes by the treatment of Riemann's problem which represents the system of PDEs with constant initial conditions on both sides of this discontinuity. That operation is difficult. This imposes the use of numerical techniques. In our case, the choice of finite volume method is dictated by the conservative nature of Saint-Venant's equations.

In this study, we explored first order Godunov's

scheme, second-order Lax-Wendroff scheme without limiters and second order slope limiters' schemes such as: Minmod, Superbee, Van Leer and Monotonized Centered schemes. From numerical tests and analysis of transitory and stationary flows, we note that slope limiters' schemes are most advantageous. They yield more accurate and stable solutions. Finally, we envisage introducing friction effects to examine real cases.

Acknowledgements

Clawpack software is written by Randall J. Le Veque, University of Washington. But we made modifications for the applications quoted on the top.

Notations

A	-	Jacobian matrix;
$b(x)$	-	Bottom function;
CI	-	Elementary cell;
F	-	Flux vector terms through interfaces;
Fr	-	Froude's number;
$f(q)$	-	Flux function;
g	m/s^2	Gravitational acceleration;
h	m	Depth of water;
hu	m^2/s	Unit discharge;
Q	-	Conservative variables vector;
q_t	-	Partial differential in time;
q_x	-	Partial differential in space;
Q_i^n	-	Approximation of the dependent variable;
t	s	Time;
u	m/s	Average velocity;
x	-	Longitudinal co-ordinate;
ψ	-	Source terms vector;
\emptyset	-	Flux limiter function.

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